Round 1 Emissions Results from Compressed Natural Gas Vans and Gasoline Controls Operating in the U.S. Federal Fleet

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ABSTRACT

The first round of emissions testing of light-duty alternative fuel vehicles placed in the U. S. federal fleet under the provisions of the Alternative Motor Fuels Act was recently completed. This undertaking included 75 Dodge B250 vans, of which 37 were dedicated compressed natural gas models, and 38 were standard gasoline controls. Data were collected on regulated exhaust emissions using the federal test procedures, and on a number of other quantities, through a statistically controlled program of investigation. Fuel economy results were also recorded. All test vehicles were operated in routine federal service activities under normal working conditions, adhering as closely as possible to Chrysler's prescribed maintenance schedules.

The data analysis conducted thus far indicates that the compressed natural gas vehicles exhibit notably lower regulated exhaust emissions, on average, than their gasoline counterparts, and that these values are well within U.S. Environmental Protection Agency standards. In addition, lower levels of toxic constituents are emitted by the compressed natural gas vehicles relative to their gasoline counterparts, and they produce lower levels of ozone precursors as well—both characteristics that are highly desirable in contemporary transportation fuels. The compressed natural gas vehicles obtain slightly lower fuel economy than their gasoline counterparts on an energy equivalent basis.

To promote the use of alternative fuels and development of an alternative fuel vehicle (AFV) industry, the Alternative Motor Fuels Act (AMFA) of 1988 requires the U.S. federal fleet to include as many AFVs as practicable. The Energy Policy Act (EPACT) of 1992 tightened the requirements for the federal fleet, requiring new vehicle purchases to be comprised of an increasing percentage of AFVs, up to a maximum of 75%, by 1999. The U.S. Department of Energy is responsible for tracking and reporting the performance of these vehicles on an annual basis to facilitate ongoing evaluation of AFV technology, and for assessing the viability of AFVs in commercial and private applications. Performance measures include driver acceptance, fuel economy, operational cost, cost and level of maintenance, and emissions output.

The most extensive effort of its kind, the AMFA evaluation program targets three alternative fuels—methanol, ethanol, and compressed natural gas (CNG)—and encompasses several different types of vehicles, makes, and models operated in a number of federal service applications at various sites around the country. Light-duty passenger cars, vans, and trucks are included, along with school buses, transit buses, and heavy-duty trucks. The earliest AMFA vehicles have been in service since 1991.

One of the objectives of the AMFA light-duty test program is to compare the emissions of AFVs in actual service to those of otherwise identical vehicles operating on conventional fuel. Detection of emissions deterioration as a result of age and use is of particular interest. In all cases, reformulated gasoline (RFG) is used as the basis of comparison in laboratory tests.

This paper specifically addresses the emissions performance of light-duty federal fleet AFVs operating on CNG. The information reported here covers emissions test results from 75 Dodge RAM B250 vans, 37 of which are dedicated CNG models, with the remaining 38 being standard gasoline versions (controls). The data represents results solely from Round 1 of a three-round testing program (hence, emissions deterioration is not specifically addressed).

TEST VEHICLES

As depicted in Figure 1, the test vehicles are 1992 and 1994 model year Dodge B250 full-size, 15-passenger vans. General vehicle characteristics are summarized in Table 1.

Both the CNG and gasoline models are configured with 5.2-liter V-8 engines, multi-point fuel injection systems, and 4-speed automatic transmissions. The CNG model is reported by Chrysler to be certified as a low emission vehicle (LEV) by virtue of its having been equipped with a special natural gas catalyst for low emissions.

The primary difference in the physical characteristics of the two vehicles is fuel capacity. The gasoline model is equipped with a 35-gallon fuel tank (a 22-gallon tank is standard), whereas the CNG model carries three or four fuel cylinders, yielding an onboard fuel capacity of 11.1 equivalent gallons for the three-cylinder configuration, and 15.7 equivalent gallons for the four-cylinder configuration. As a result, curb weight is increased, and driving range is decreased, for the CNG model.

Table 1 - Operational characteristics of Dodge B250 vans

CNG	Gasoline
• 5.2 Liter V-8 Engine Configuration	• 5.2 Liter V-8 Engine Configuration
• Multi-Point Fuel Injection	• Multi-Point Fuel Injection
• 4-Speed Automatic	• 4-Speed Automatic
• 11.1–15.7 Equivalent Gallon Fuel Capacity (Optional 4th Fuel Tank)	• 35–Gallon Tank Option (22–Gallon Tank Standard)
• Range: City 100–150 Miles; Highway 150–200 Miles	• Range: City 285–455 Miles; Highway 375–595 Miles
• Weight GVW ~6,400 lbs; Curb ~4,580 lbs; ALVW ~5,490 lbs (Optional 4th Tank Adds Weight)	• Weight GVW ~6,400 lbs; Curb ~4,000 lbs; ALVW ~5,150 lbs
• LEV-Certified (Equipped with Special Natural Gas Catalyst for Low Emissions)	

Figure 1. Photo of Dodge B250 full-size, 15-passenger van

EXPERIMENTAL DESIGN

The CNG component of the AMFA light-duty emissions testing program was originally designed to encompass a total of 80 vehicles—40 AFVs and 40 gasoline controls. Vehicle testing was split between two different independent laboratories—ManTech Environmental Technology, Inc., in Denver, Colorado, and Environmental Research and Development, Corp. in Gaithersburg, Maryland—selected through a competitive bidding process. The Denver site was chosen to provide some sense of high-altitude effects. Each laboratory was assigned half of the targeted 80 vehicles as a test load; that is, 20 AFVs and 20 gasoline controls each.

Vehicles were selected at random for participation in the testing program from all those available in the federal geographic service area(s) closest to each laboratory's test facilities. All vehicles were originally purchased by the U.S. General Services Administration (GSA) from Chrysler and leased to various federal agencies. No modification was made to the vehicle selection procedure to specifically control for anticipated variations in vehicle service activities and functions (which may range from short delivery routes to highway driving), mileage age (odometer reading) of the vehicle when selected for participation, or service, maintenance, and refueling practices attributable to different federal installations. Adherence to Chrysler's recommended preventive maintenance schedule at all installations was assumed.

The experimental design includes testing each vehicle at multiple mileage increments using identical fuels (see the discussion below concerning fuel composition). Over the life of the program, each vehicle is scheduled for emissions testing by its assigned laboratory at approximately 4,000 miles, approximately 10,000 miles, and at subsequent increments of approximately 10,000 miles. Vehicles are continuously operated in their normal service functions until they reach these approximate mileage levels, at which time they are called in and driven to the laboratory site for testing.

In addition to conducting multiple tests over time, each laboratory was instructed to conduct replicate measurements on a minimum of four vehicles (two each of the CNG and gasoline models) at each of the target mileage intervals for purposes of assessing laboratory repeatability. Also, vehicles were re-tested if their emissions output at any target mileage level exceeded the U.S. Environmental Protection Agency (EPA) Tier 0 standards. No vehicles were cross-tested by both labs.

TEST PROCEDURES

The emissions testing program itself was designed to provide the most accurate and precise measurements possible using the EPA's federal test procedure (FTP) [1]. For the CNG vehicles, the regimen included the collection of exhaust emissions using the FTP, evaporative emissions using a simplified version of the EPA's sealed housing evaporative determination (SHED) for leakage (both diurnal and hot soak), and speciated exhaust hydrocarbons (toxic compounds and ozone precursors) from a number of vehicles equal to approximately 15% of all the vehicles tested for exhaust emissions by one of the labs (in this case, speciation constitutes identification and quantification of the non-oxygenated exhaust constituents using gas chromatography). ManTech Environmental Technology, Inc. was designated to provide speciation results. The evaporative emissions tests were included because of concerns expressed by some drivers and service technicians that the existence of leaks in the fuel systems of CNG vehicles could result in a hazardous buildup of gases in enclosed parking spaces or maintenance facilities.

For the gasoline vehicles, a similar regimen was followed: collection of both exhaust and evaporative emissions using the FTP, and speciated exhaust hydrocarbons (toxics and ozone precursors) on a number of vehicles equal to approximately 15% of all the vehicles tested for exhaust emissions by one of the labs. Again, ManTech Environmental Technology, Inc. was designated to provide speciation results. Because of potential differences in the characteristics of the fuels on which the individual vehicles actually operate, the test procedures for gasoline vehicles included a fuel-flushing change-out routine to remove fuel carry-over effects similar to the one used in the Auto/Oil program [2].

The emissions test procedures are designed to be essentially identical across laboratories. However, to ensure the full integrity of the data, EPA has conducted an audit of the test procedures and emissions calculations used by the two labs. Although the tests conducted by ManTech Environmental Technology, Inc. obviously yield high-altitude results, it is not possible to statistically distinguish the effect of altitude from differences between labs.

FUEL COMPOSITION

Uniformly blended fuels are prepared for use in the emissions testing program, and vehicles are tested using the same fuel at each designated mileage level. The CNG is blended by National Specialty Gases, and is designed to represent industry average fuel composition. Table 2 lists the concentrations of various constituents in the gas. California Phase 2 reformulated gasoline (RFG), blended by Phillips Petroleum Company, is used in tests on the control vehicles. The composition of the fuels actually used in the vans during normal day-to-day activities is unknown.

TEST FLEET CHARACTERISTICS: EXHAUST AND EVAPORATIVE EMISSIONS

Actual vehicle selection resulted in 37 CNG vans and 38 gasoline vans (controls) being chosen for participation in the exhaust and evaporative emissions testing program. Of the 37 CNG vans, 34 (92%) were 1992 models, and 3 were 1994 models. Conversely, of the 38 gasoline controls, 17 (45%) were 1992 models and 21 were 1994 models. Of the 75 total vehicles in the program, 33 (16 CNG models; 17 gasoline models) are in service in the Washington, D.C. metropolitan area; 10 (5 CNG models; 5 gasoline models) are in service in the metropolitan New York City and northern New Jersey areas; and 32 (16 CNG models; 16 gasoline models) are in service in the Denver metropolitan area. ManTech Environmental Technology, Inc. tested all vehicles from Denver, and Environmental Research & Development tested all vehicles from Washington, D.C. and the New York area. Table 3 shows a breakdown of all 75 test vehicles according to type, model year, and service location.

TEST FLEET CHARACTERISTICS: TOXIC EXHAUST EMISSIONS AND SPECIATED HYDROCARBONS

Actual vehicle selection resulted in two CNG vans and three gasoline vans (controls) being designated for speciation of exhaust hydrocarbons to determine the levels of toxic pollutants and ozone precursors. Unfortunately, for logistical and operational reasons, none are represented in the exhaust/evaporative data set described above.

All vans were 1992 model year vehicles. All five vehicles were in service in the Denver area and were tested by ManTech Environmental Technology, Inc.

VEHICLE MILEAGE ACCUMULATION AND OTHER DATA SET CHARACTERISTICS

Because the emissions testing program is in continuous operation, results obtained in the first calendar year of operation include measurements on some vehicles at both the initial and second target mileage levels. The series of tests on the vehicles at a particular target mileage level are referred to as rounds. All the results being reported at this time represent the initial measurements taken on the vehicles (Round 1). In particular, the data set comprises results from 86 exhaust emissions tests conducted on 75 vehicles during the period of March 17, 1994, to May 11, 1995. Included in this data set are a small number of replicate and/or repeat test measurements on selected vehicles, although no assessment of laboratory repeatability is reported here.

Evaporative emissions tests were not conducted on all the vehicles during the first year of program operation. Consequently, the Round 1 data set contains results from only 67 evaporative emissions tests conducted on the 75 vehicles. There were four replicates, or repeat, evaporative measurements.

For exhaust and evaporative emissions, Table 4 shows a breakdown, by lab and vehicle type, of the number of vehicles compared to the number of tests, and identifies the number of replicates and/or repeat tests included. For the speciated exhaust hydrocarbons, one test was performed per vehicle. All results are presented here exactly as reported by the labs, without any values having been edited or removed.

Obviously, for logistical reasons, not all vehicles can be tested at exactly the target mileage levels. The vehicle odometer readings at the time of the initial exhaust tests ranged from a low of 2,121 to a high of 30,493, with an average initial mileage accumulation of 10,047. The vehicle odometer readings associated with the information on speciated hydrocarbons ranged from a low of 5,271 to a high of 10,123, with an average of 8,299.

Table 5 contains a complete breakdown of mileage accumulation, by vehicle type, on vehicles for which exhaust

Table 2 - Compressed natural gas (CNG) composition

Component	Specification	Typical Ratio Analysis Concentration*
Methane	93.05%	Balance
Ethane	3.47%	13.55%
Nitrogen	1.67%	1.59%
Carbon Dioxide	0.81%	0.834%
Propane	0.66%	0.664%
N-Butane	0.12%	0.0638%
I-Butane	0.08%	0.1087%
N-Hexane	0.06%	0.0638%
I-Pentane	0.04%	0.0490%
N-Pentane	0.03%	0.0499%
Oxygen	0.00%	0.00%

*gas chromatograph analysis
280 standard-cubic feet cylinders, pressured to 2000 psi
+/-1% blend tolerance; +/-1% analytical tolerance

Table 3 - Fleet characteristics of vehicles tested for exhaust and evaporative emissions

Model Year	In-Service Location	Vehicle Type CNG	Vehicle Type Gasoline	Total
1992	Washington, D.C.	13	0	13
	Denver	16	12	28
	New York/New Jersey	5	5	10
	Subtotal	**34**	**17**	**51**
1994	Washington, D.C.	0	17	17
	Denver	3	4	7
	New York/New Jersey	0	0	0
	Subtotal	**3**	**21**	**24**
All Years	Washington, D.C.	16	17	33
	Denver	16	16	32
	New York/New Jersey	5	5	10
	Total	**37**	**38**	**75**

emissions tests were conducted, vehicles which received evaporative emissions tests, and vehicles for which speciated exhaust hydrocarbons were developed. As previously noted, not all vehicles tested for exhaust emissions were tested for evaporative emissions.

Figure 2 graphically depicts the mileage levels attained by the various vehicles tested for exhaust emissions. A comparison is shown for the two types of vans. Repeat tests are included. The figure indicates that the mileage distributions for initial, Round 1 exhaust tests are somewhat different for the CNG and gasolinevans, the CNG vans generally having been tested earlier in their service lives.

EXPERIMENTAL RESULTS

Tables containing the actual measurements of the emissions constituents obtained from the Round 1 tests are provided in the Appendix. Exhaust constituents include nonmethane

Table 4. Comparison of the numbers of vehicles tested and the numbers of tests completed for exhaust and evaporative emissions

Vehicle Type	Lab	Vehicles	Exhaust Tests	Evaporative Tests
CNG	1	16	19	7
	2	21	23	17
	Both	37	42	24
Gasoline	1	16	20	19
	2	22	24	24
	Both	38	44	43
Total		75	86	67

Notes: Replicate exhaust tests were conducted on a total of 10 vehicles (5 CNG, 5 gasoline). Replicate evaporative tests were conducted on a total of 4 vehicles (all gasoline).

Table 5. Comparison of mileage accumulation on all vehicles tested

Test	Vehicle Type	Low (miles)	High (miles)	Average (miles)
Exhaust	CNG	2,121	22,272	7,964
	Gasoline	3,527	30,493	12,035
	Both	2,121	30,493	10,047
Evaporative	CNG	2,121	15,091	7,945
	Gasoline	3,527	30,493	12,106
	Both	2,121	30,493	10,616
Speciated Hydrocarbons	CNG	5,271	9,514	7,393
	Gasoline	7,287	10,123	8,903
	Both	5,271	10,123	8,299

hydrocarbons (NMHC), carbon monoxide (CO), carbon dioxide (CO_2), and oxides of nitrogen (NO_x). Evaporative emissions are expressed only as total hydrocarbons (THC). Fuel economy values are also provided. Table 6 provides descriptive statistics on each of these quantities.

Speciated hydrocarbons are reported in the Appendix as ozone-forming potential (OFP) and specific reactivity (SR). The tables also include values of the four exhaust constituents, along with an aggregate of the four, designated by the Clean Air Act Amendments of 1990 as mobile source toxics: benzene (C_6H_6); 1,3-butadiene (C_4H_6); formaldehyde (HCHO); and acetaldehyde (CH_3CHO). Table 7 contains average values for each of these quantities.

OFP and SR are calculated using the Carter [3] method, which encompasses the regulatory requirements adopted by the State of California. Using this approach, a maximum incremental reactivity (MIR) value is assigned to individual exhaust constituents. This MIR value represents the predicted impact of the respective constituent on urban atmospheric ozone formation, expressed as milligrams of ozone per milligram of the constituent. OFP for a specific fuel is computed by incorporating the MIR values for all constituents measured in the exhaust from that fuel. SR for a specific fuel is calculated by combining the respective masses of the constituents measured in the exhaust from that fuel, on a per-mile basis, with the corresponding value of OFP. Under

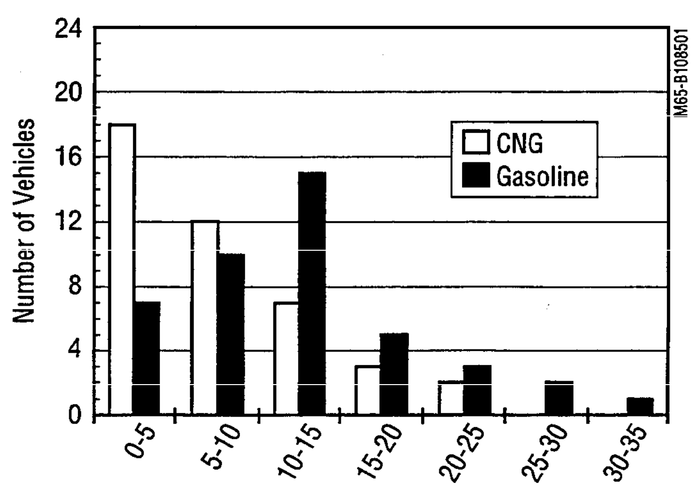

Figure 2. Round 1 mileage accumulation on two types of vehicles tested for exhaust emissions (includes repeat tests)

Table 6. Descriptive statistics for fuel economy, exhaust emissions, and evaporative emissions

Lab	Vehicle Type	Statistic	Fuel Economy (mi/gal)	CO (g/m)	CO_2 (g/mi)	NMHC (g/mi)	NO_x (g/mi)	Evaporative THC (g/test)
1	CNG	Min.	11.00	0.47	526.10	0.02	0.07	0.05
		Max.	12.40	4.80	586.70	0.10	1.20	1.46
		Std. Dev.	0.33	1.19	14.86	0.02	0.32	0.44
		# Vehicles*	21	21	21	21	21	17
		Avg.	11.54	1.99	563.54	0.05	0.54	0.38
	Gasoline	Min.	12.04	4.03	635.03	0.23	0.39	0.35
		Max.	13.79	9.68	726.43	0.43	1.02	1.04
		Avg.	13.10	5.83	666.85	0.29	0.78	0.59
		Std. Dev.	0.51	1.62	76.44	0.05	0.16	0.19
		# Vehicles*	22	22	22	22	22	22
2	CNG	Min.	12.51	0.51	436.66	0.02	0.09	0.06
		Max.	15.55	18.31	539.27	0.18	1.55	2.50
		Avg.	13.47	3.65	500.58	0.06	0.48	0.57
		Std. Dev.	0.65	4.29	22.80	0.04	0.45	0.87
		# Vehicles*	16	16	16	16	16	7
	Gasoline	Min.	13.00	0.74	587.02	0.21	0.49	0.25
		Max.	14.60	4.82	660.96	0.32	1.12	8.21
		Avg.	13.91	3.76	617.27	0.26	0.70	1.42
		Std. Dev.	0.47	0.95	21.31	0.03	0.17	1.86
		# Vehicles*	16	16	16	16	16	16

*All replicate and repeat tests are averaged.

Table 7. Average values for toxic pollutants and ozone precursors

Vehicle Type	C_6H_6 (mg/mi)	C_4H_6 (mg/mi)	HCHO (mg/mi)	CH_3CHO (mg/mi)	Aggregate Toxics (mg/mi)	OFP (mg ozone/ mi)	SR (mg ozone/ mg NMOG)
CNG	0.70	0.10	6.28	0.39	7.47	294.05	2.04
Gasoline	10.30	1.93	3.26	1.02	16.31	1,149.41	4.08

California regulations, SR is based on non-methane organic gas(NMOG) emissions rather than total organic gas emissions.

The discussion that follows compares and contrasts the Round 1 test results for all the emissions constituents identified above. Of specific interest are the differences in emissions profiles for the CNG vans versus those of the gasoline vans. Differences in the values of fuel economy and of the emissions test results obtained by the two independent labs are also of interest. In the figures and discussion below, the two labs are referred to as Lab 1 and Lab 2.

Where appropriate, all exhaust test results are related to the Tier 1 federal emissions standards for heavy light-duty non-diesel vehicles. These standards (for in-use tailpipe emissions at approximately 50,000 miles) are graphically depicted in Figure 3 for two different vehicle weights (adjusted loaded vehicular weight, or ALVW).

FUEL ECONOMY - A lab-by-vehicle type comparison of fuel economy is presented in Figure 4. For this study, all fuel economy values were calculated from measurements obtained on the vehicles during chassis dynamometer testing (as opposed to being in-use values). Calculations for fuel economy follow the procedures published in the Federal Register [1] and recommended by the EPA's certification facility in Ann Arbor, Michigan.

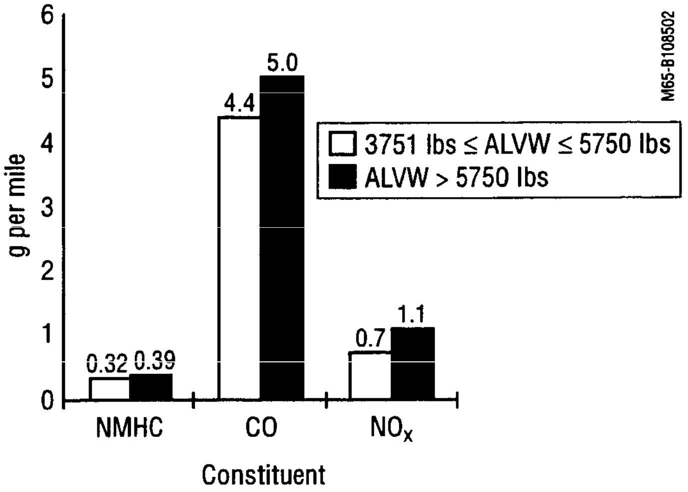

Figure 3. Federal exhaust emissions standards for heavy light-duty non-diesel vehicles (Tier 1, tailpipe in-use, 50,000 miles)

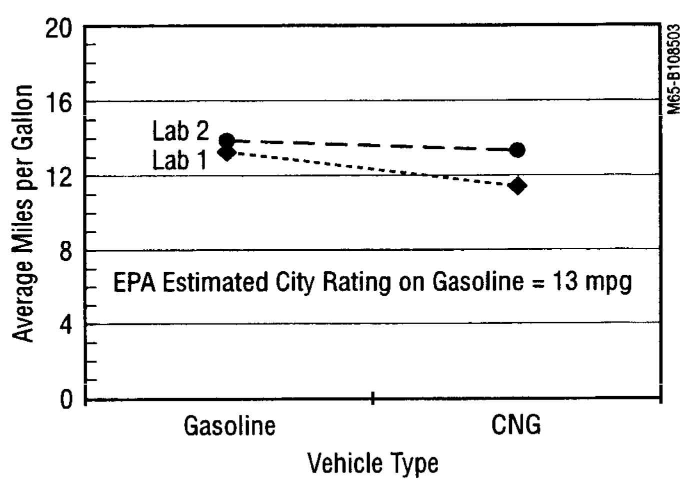

Figure 4. Comparison of fuel economy for the two types of vehicles, by lab

On average, the gasoline vans obtained higher fuel economy than the CNG vans, a finding that was repeated in the results reported by both labs. The fuel economy determined for gasoline vans was 13.10 miles per gallon and 13.91 miles per gallon for Labs 1 and 2, respectively, and the fuel economy determined for CNG vans was 11.54 miles per gallon and 13.47 miles per gallon for Labs 1 and 2, respectively. Since the EPA-estimated city rating for Dodge B250 vans on gasoline is 13 miles per gallon, only the average for the CNG vans tested by Lab 1 might be considered outside an acceptable range.

EXHAUST EMISSIONS - Comparisons of the CO, CO_2, NO_x, and NMHC emissions measured by the two labs on the two types of vehicles are presented in Figures 5 through 8, respectively. The corresponding Tier 1 federal standards are shown superimposed on the figures. CO_2 is not a regulated component, and therefore, no standards are available for comparison.

Figure 5 compares the CO emissions, stated as average grams per mile, reported by the two labs for the two types of vehicles. The federal Tier 1 standard for CO is 4.4 grams per mile. The figure indicates a considerable difference in the results obtained by the two labs on the two types of vehicles. In the case of the gasoline vans, Lab 1 reported higher average CO emissions (5.83 grams per mile) than Lab 2 (3.76 grams per mile); whereas for the CNG vans, Lab 1 reported lower average CO emissions (1.99 grams per mile) than Lab 2 (3.65 grams per mile). Lab 2 reported only the slightest reduction in CO emissions from CNG vans compared to those from gasoline vans, although its CNG average was dominated by a single van with a very high value. Only the results from Lab 1 for gasoline vans exceed the federal Tier 1 standard of 4.4 grams per mile; and the results from CNG vans tested at both labs are considerably below the standard.

Figure 6 shows the vehicle-type comparison of CO_2 emissions reported by the two labs, stated as average grams per mile. The results for Lab 2 are lower than those for Lab 1 for both

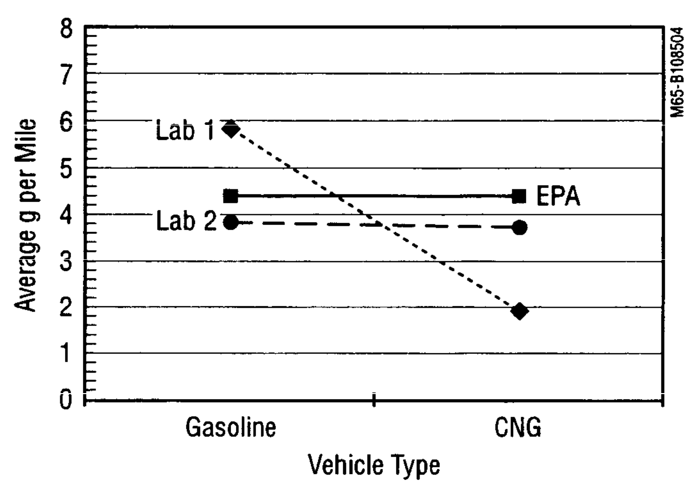

Figure 5. Comparison of CO emissions from the two types of vehicles, by lab

vehicle types, although both labs reported lower CO_2 emissions from the CNG vans (563.54 grams per mile and 500.58 grams per mile for Labs 1 and 2, respectively) than from the gasoline vans (666.85 grams per mile and 617.27 grams per mile for Labs 1 and 2, respectively).

Generally speaking, a reduction in CO_2 emissions corresponds to an increase in fuel economy. However, as indicated in Figure 4, the CNG vans obtained lower fuel economy while simultaneously emitting lower levels of CO_2 than their gasoline counterparts (see Figure 6). This finding may suggest that these particular

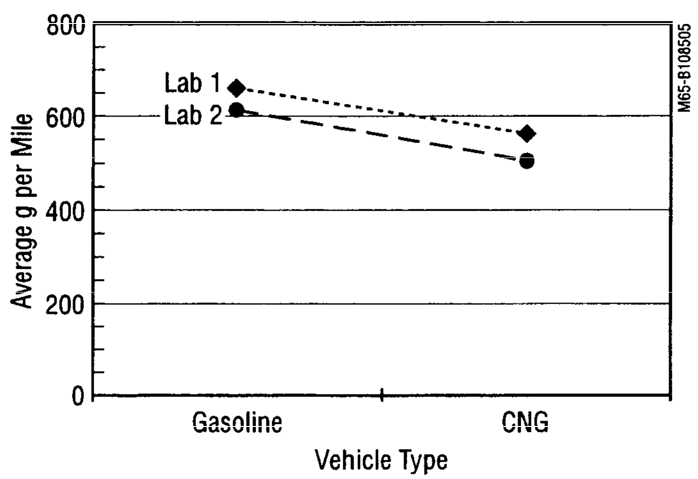

Figure 6. Comparison of CO_2 emissions from the two types of vehicles, by lab

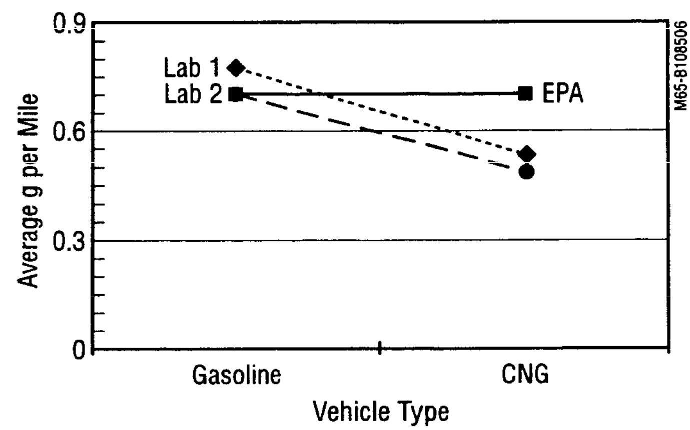

Figure 7. Comparison of NO_x emissions from the two types of vehicles, by lab

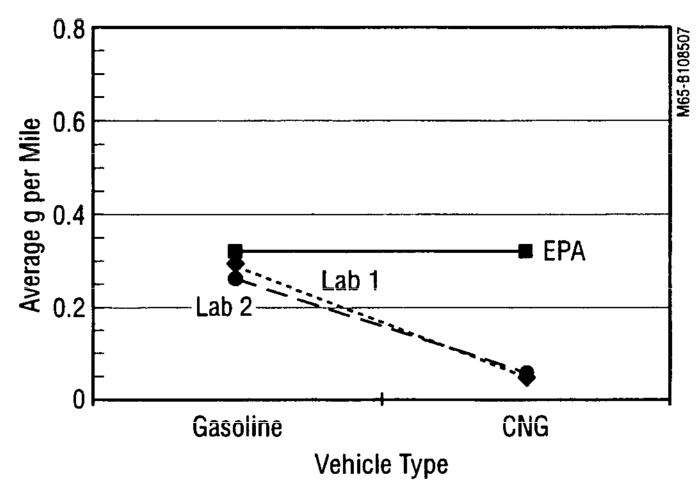

Figure 8. Comparison of NMHC emissions from the two types of vehicles, by lab

vehicles are inherently lower emitters of CO_2, an important greenhouse gas.

Figure 7 compares the NO_x emissions, stated as average grams per mile, reported by the two labs for the two types of vehicles. The federal Tier 1 standard for NO_x is 0.70 grams per mile. For the gasoline vans, Lab 2 reported an average of 0.70 grams per mile, a value equal to the standard, whereas Lab 1 reported an average of 0.78 grams per mile, a value slightly higher than the standard. The values for CNG vans reported by both labs(0.54 grams per mile and 0.48 grams per mile for Labs 1 and 2, respectively) are considerably lower than the corresponding values for gasoline vans, and they are also considerably lower than the standard.

Figure 8 shows the vehicle-type comparison of NMHC emissions reported by the two labs, stated as average grams per mile. The federal Tier 1 standard for NMHC is 0.32 grams per mile. The results reported by the two labs fall below the standard for both gasoline (0.30 grams per mile and 0.26 grams per mile for Labs 1 and 2, respectively) and CNG (0.05 grams per mile and 0.06 grams per mile for Labs 1 and 2, respectively) vans, and the CNG results are considerably lower than the gasoline results.

EVAPORATIVE EMISSIONS - A comparison of evaporative THC measured on the two types of vehicles by the two labs is presented in Figure 9. There is no federal standard for THC.

In the case of evaporative emissions, those reported by Lab 1 are lower, on average, than the results reported by Lab 2 for both gasoline and CNG vans (for exhaust emissions, the results from Lab 2 tend to be the lower ones). The more important finding, however, is that average evaporative THC reported from CNG vans is lower by a considerable margin than the corresponding average value reported from gasoline vans (a range of 0.38 - 0.57 grams per test for the two labs versus a range of 0.59 - 1.42 grams per test for the two labs, respectively). In addition to the obvious emissions benefit, this result specifically serves to counter the suggestion that the fuel system on the CNG vehicles poses a safety risk.

TOXIC EXHAUST EMISSIONS - Figures 10 through 13 present vehicle-type comparisons of the four mobile source toxic exhaust compounds: benzene (C_6H_6); 1,3-butadiene (C_4H_6); formaldehyde (HCHO); and acetaldehyde (CH_3CHO). All results are reported in average milligrams per mile. Figure 14 compares the average aggregated toxic emissions for the two types of vehicles.

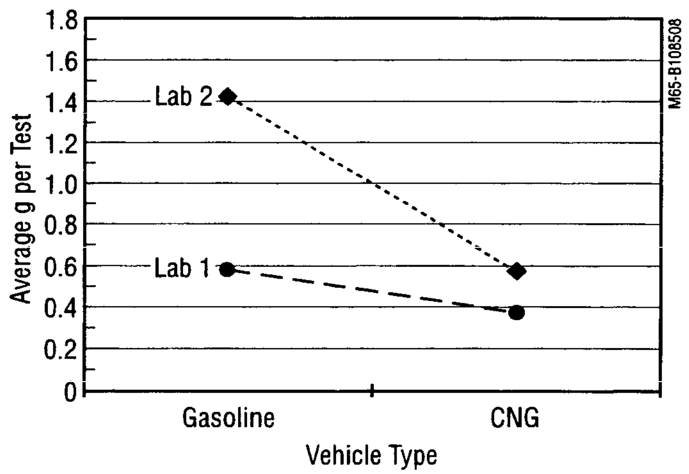

Figure 9. Comparison of evaporative THC measured on the two types of vehicles, by lab

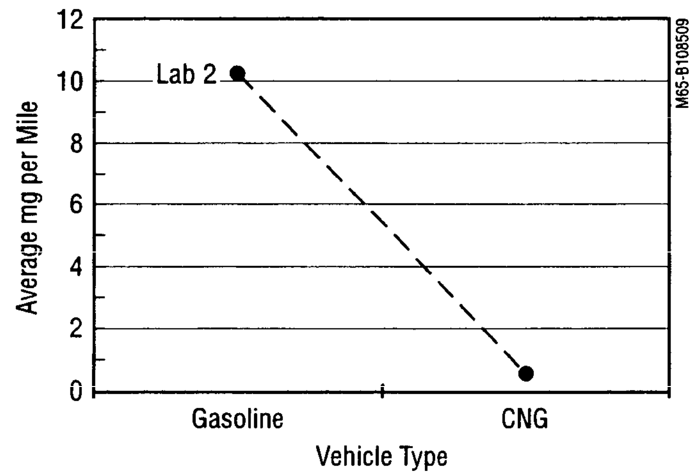

Figure 10. Comparison of C_6H_6 emissions from the two types of vehicles

As noted above, the Round 1 toxic emissions data set is a relatively sparse one—only two CNG vehicles and three RFG vehicles are included, with a single test having been performed on each vehicle. Further, one of the two CNG vehicles is known to exhibit an abnormally high emissions profile, which may adversely impact all average results.

In all cases except for formaldehyde, the results show that the levels of toxic compounds emitted from the CNG vans are substantially lower, on average, than those from the gasoline vans (with the caveat that data was obtained from only a small number of vehicles). Similarly, the average of the aggregated toxic emissions for the CNG vans is 7.47 milligrams per mile, while it is 16.31 milligrams per mile for the gasoline vans.

The Clean Air Act Amendments of 1990 specify that reformulated gasoline must produce at least a 15% reduction in aggregated toxic emissions. Assuming the RFG used here satisfies this requirement, the aggregate of the toxic emissions for the CNG vans represents an incremental 54% reduction, on average.

In the case of formaldehyde, the average value reported for the CNG vehicles is higher than the corresponding value reported for the gasoline vehicles. However, the CNG average includes a very high data point obtained on the single suspect van (10.78 milligrams per mile versus 1.78 milligrams per mile). This situation closely parallels the circumstances recently reported by Gabele [4]. In that study, the aggregate toxic emissions from two 1992 Dodge CNG vans averaged 6.25 milligrams per mile, with one of the two also emitting a much higher level of formaldehyde (8.36 milligrams per mile, on average, versus 1.55 milligrams per mile, on average).

In summary, as is the case for evaporative and regulated emissions, CNG vans generally exhibit lower levels of toxic emissions than their gasoline counterparts.

OZONE PRECURSORS - Ozone precursor data are reported in terms of OFP and SR. Figures 15 and 16 show the respective comparisons for these two quantities for the two types of vehicles. As in the case of the toxic emissions, the data set for ozone precursors encompasses only a small number of results—a single value obtained on each of the two CNG vans and three gasoline vans.

OFP is reported in average milligrams of ozone per mile, and SR is reported as an average of milligrams of ozone per milligrams of non-methane organic gas (NMOG). There are no federal standards for comparison purposes.

Generally speaking, OFP will be high when SR is high and there is a high overall emissions output. However, for CNG vehicles, OFP can also be low in this situation. Such incongruity is attributable to the fact that NMHC emissions can be extremely low while SR, a calculated quantity, is still quite high. Black and Kleindienst [5], for example, suggest that values of SR from low-emitting CNG vehicles can be higher than those from gasoline vehicles; and that CNG vehicles with high NMHC emissions can exhibit low values of SR because those emissions predominantly consist of compounds such as ethane which have low reactivity.

In the present study, OFP and SR are both substantially lower, on average, for the CNG vans than for their gasoline counterparts. Average OFP for the gasoline vans is 1149.41 milligrams of ozone per mile, whereas for the CNG vans it is 294.05 milligrams

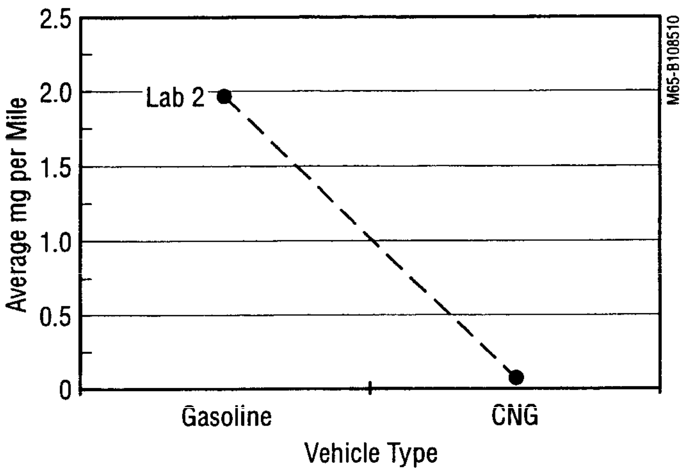

Figure 11. Comparison of C_6H_6 emissions from the two types of vehicles

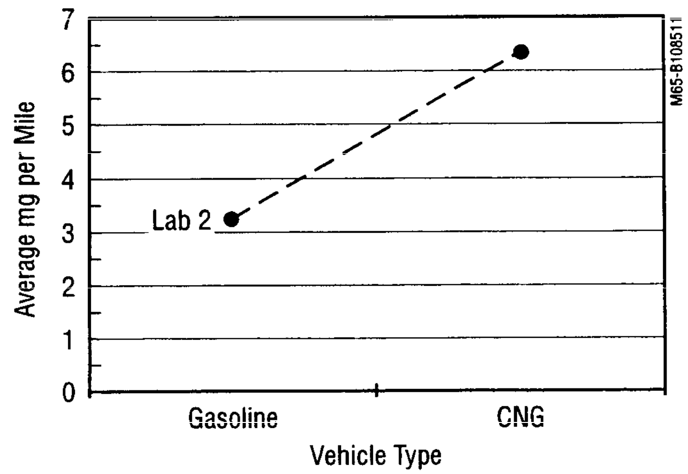

Figure 12. Comparison of HCHO emissions from the two types of vehicles

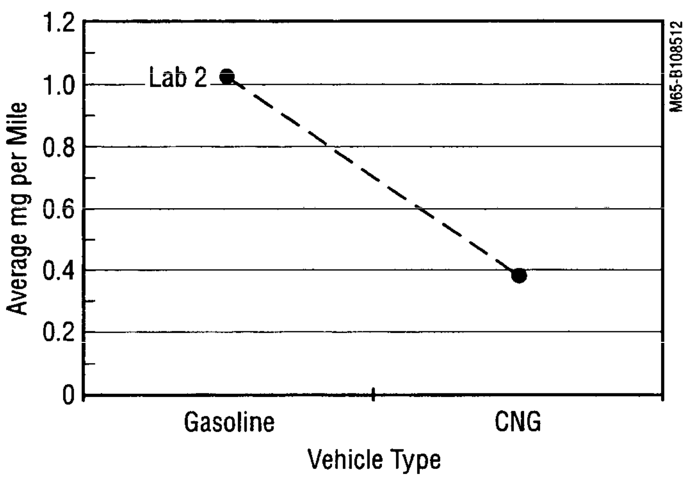

Figure 13. Comparison of CH_3CHO emissions from the two types of vehicles

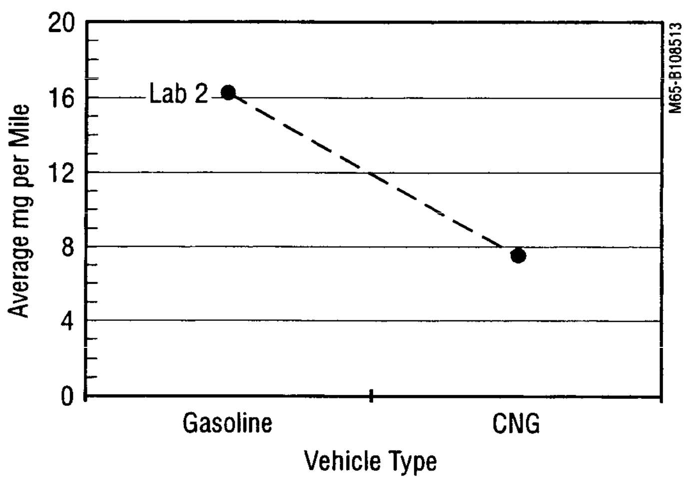

Figure 14. Comparison of aggregated toxic emissions for the two types of vehicles

of ozone per mile—the difference being approximately an order of magnitude. Average SR is 4.08 milligrams of ozone per milligram of NMOG for the gasoline vans, whereas it is 2.04 milligrams of ozone per milligram of NMOG for the CNG vans.

Again, with the caveat that data was obtained from only a small number of vehicles, the CNG vans exhibit lower levels of ozone precursors than their gasoline counterparts.

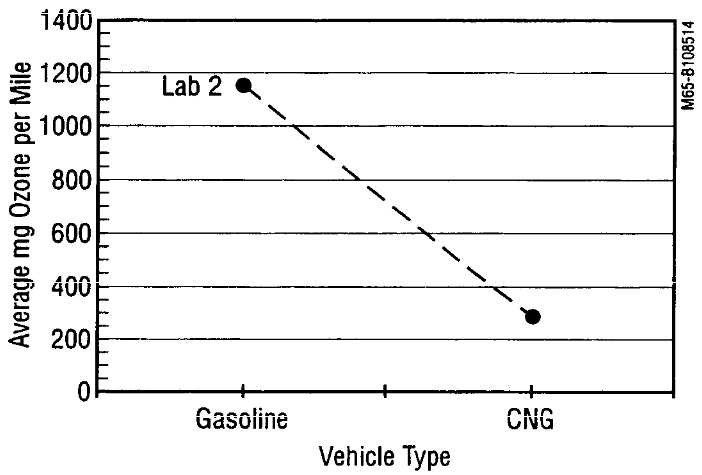

Figure 15. Comparison of OFP calculated for the two types of vehicles

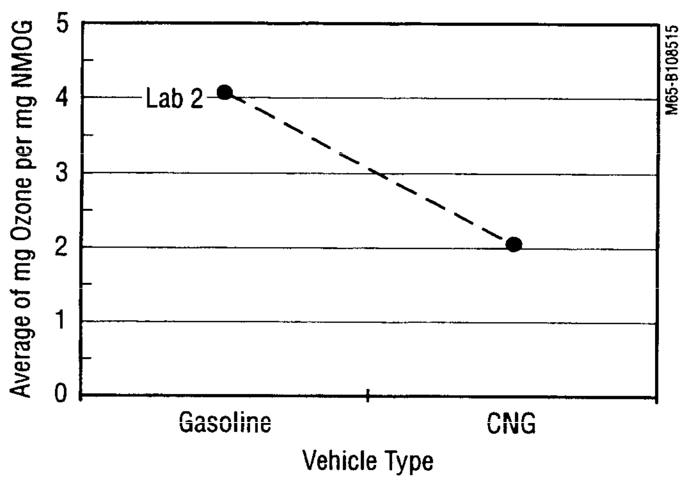

Figure 16. Comparison of SR calculated for the two types of vehicles

SUMMARY OF RESULTS

For each of the quantities discussed above, Table 8 shows the percent change in the average results reported for the CNG vans relative to their gasoline counterparts. An individual tabulation is presented for both labs. Note again that the results for toxic pollutants and ozone precursors are associated with a different set of vehicles than the results for fuel economy, exhaust emissions, and evaporative emissions.

Table 8. Percent change in average emissions and fuel economy for CNG vehicles relative to gasoline vehicles

Quantity	% Change Lab 1	Lab 2
fuel economy	-11.9	-3.2
NMHC	-83.3	-76.9
CO	-65.9	-2.9
NO_x	-30.8	-31.4
CO_2	-15.5	-18.9
THC	-35.6	-59.9
OFP	-74.4	*
SR	-50.0	*
C_6H_6	-96.0	*
C_4H_6	-94.8	*
HCHO	48.0	*
CH_3CHO	-61.8	*
*No Measurements		

Overall, the Round 1 results from the federal emissions testing program indicate that the dedicated CNG vans exhibit notably lower regulated exhaust emissions profiles than their gasoline counterparts, with all constituents well within EPA standards. These vehicles also emit moderately lower amounts of CO_2, on average, than the gasoline vehicles. On the other hand, energy equivalent fuel economy is also lower, on average, for the CNG vans than for the gasoline vans.

There is some evaporative emissions leakage associated with the CNG fuel systems, but the mass is no more than would typically be expected from evaporative emissions in a corresponding gasoline vehicle. Any such leakage primarily consists of methane, a non-reactive and non-toxic compound which arises from many sources and is naturally released into the atmosphere. This finding serves to mitigate the safety concerns raised about the CNG fuel system technology.

The CNG vans from which the speciated exhaust emissions profile was developed exhibit substantially lower OFP and SR than their gasoline counterparts. In addition, with the caveat that the formaldehyde results are discounted (see the discussion above), these vans also emit levels of toxic pollutants that are substantially lower than those of their gasoline counterparts. The reduced levels of ozone precursors and toxic pollutants are both highly desirable characteristics of contemporary transportation fuels; and the findings of lower reactivity and lesser amounts of toxics are additional mitigating factors relative to concerns about CNG vehicle safety.

Most vehicles in this study will continue to be monitored to determine if there is any deterioration in emissions levels as the equipment ages. Future reports will discuss the effects of mileage accumulation. Further, statistical analyses are ongoing to evaluate other factors, such as laboratory differences, which may affect interpretations of the data. Some of the statistical techniques suggested by Painter and Rutherford [6] form the basis for these ongoing analysis efforts.

ACKNOWLEDGMENTS

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APPENDIX A:

Data Set Listings

Table A1. Exhaust and evaporative emissions

VEHICLE ID	HOME SITE	MODEL YEAR	LAB	TEST DATE	ODOMETER	FUEL	MPG	CO	CO_2	NMHC	NO_X	EVAPORATIVE THC
DV203GRC	DV	1992	MAN	3/21/95	29165	RFG	14.0031	4.3218	611.6371	0.261	0.8026	1.2378
DV206GRC	DV	1992	MAN	3/17/95	10962	RFG	12.9965	3.5236	660.9638	0.2294	1.1198	0.8809
DV207GRC	DV	1992	MAN	3/28/95	17687	RFG	13.7142	4.0869	625.1166	0.2487	0.6583	1.3379
DV208GRC	DV	1992	MAN	3/15/95	13012	RFG	13.6478	3.773	628.737	0.2383	0.556	0.3508
DV208GRC	DV	1992	MAN	3/17/94	10004	RFG	13.8226	4.2185	619.7857	0.3051	0.5599	0.8638
DV208GRC	DV	1992	MAN	3/18/94	10030	RFG	13.719	3.5191	625.4134	0.3778	0.5957	0.8638
DV212GRC	DV	1992	MAN	5/26/94	3875	RFG	13.4599	2.8978	639.0832	0.2102	0.5457	0.2462
DV215GRC	DV	1994	MAN	4/11/94	4325	RFG	14.0348	3.564	611.5013	0.2524	0.6234	0.8638
DV215GRC	DV	1994	MAN	4/8/94	4291	RFG	14.3051	3.8976	599.2055	0.2873	0.594	0.8638
DV216GRC	DV	1994	MAN	6/24/94	8937	RFG	13.8633	4.009	618.4273	0.2549	0.9035	0.474
DV216GRC	DV	1994	MAN	6/28/94	8963	RFG	14.2137	3.5984	603.6301	0.266	0.9029	•
DV204GRC	DV	1992	MAN	5/2/95	17831	RFG	13.2487	4.8186	646.0883	0.2798	0.5782	0.9169
DV205GRC	DV	1992	MAN	3/30/95	17130	RFG	13.3908	3.7965	640.8494	0.2475	0.7472	1.237
DV209GRC	DV	1992	MAN	4/18/95	10123	RFG	13.9582	3.58	614.9696	0.2206	0.4855	1.5237
DV210GRC	DV	1992	MAN	4/13/95	30493	RFG	14.4409	4.5459	592.4872	0.2664	0.686	1.3368
DV211GRC	DV	1992	MAN	4/20/95	27240	RFG	13.8294	4.4495	619.0143	0.3237	0.518	1.6569
DV213GRC	DV	1992	MAN	4/25/95	9300	RFG	14.1808	0.7405	609.5199	0.2637	0.7473	8.2119
DV214GRC	DV	1992	MAN	4/27/95	7287	RFG	14.6047	3.8342	587.0223	0.2305	0.6358	1.1214
DV218GRC	DV	1994	MAN	5/9/95	4110	RFG	14.5683	3.4402	589.1309	0.2317	0.7511	0.4543
DV219GRC	DV	1994	MAN	5/11/95	4484	RFG	14.2739	4.7317	599.3475	0.2355	0.8565	0.5415
DC202GRC	DC	1994	ERD	7/26/94	11449	RFG	13.69	5.6306	636.5825	0.3003	0.8617	0.5542
DC203GRC	DC	1994	ERD	8/11/94	5086	RFG	13.09	5.5072	667.4922	0.2808	0.8535	0.3826
DC204GRC	DC	1994	ERD	1/25/95	8115	RFG	13.08	5.1202	667.9077	0.2472	0.8556	0.4137
DC205GRC	DC	1994	ERD	1/19/95	3527	RFG	13.11	4.9574	667.0743	0.2624	0.7151	0.4613
DC208GRC	DC	1994	ERD	3/15/95	22195	RFG	13.32	6.7894	653.1425	0.2957	0.8748	0.6277
DC209GRC	DC	1994	ERD	7/15/94	15312	RFG	13.84	3.8402	632.7209	0.2164	0.8525	0.3249
DC209GRC	DC	1994	ERD	7/18/94	15339	RFG	13.71	4.4795	638.0411	0.2366	0.7931	0.3795
DC210GRC	DC	1994	ERD	8/3/94	10916	RFG	13.57	4.6491	643.6329	0.3121	1.0212	0.3539
DC211GRC	DC	1994	ERD	7/11/94	6277	RFG	13.78	4.4168	634.6931	0.2467	0.589	0.765
DC211GRC	DC	1994	ERD	7/12/94	6304	RFG	13.8	3.6444	635.3716	0.2457	0.5534	0.6398
DC212GRC	DC	1994	ERD	2/10/95	11374	RFG	13.2	5.6857	661.0239	0.2926	0.8825	0.517
DC213GRC	DC	1994	ERD	2/20/95	12617	RFG	12.89	5.211	678.0021	0.3022	0.7351	0.7787
DC214GRC	DC	1994	ERD	2/22/95	8136	RFG	13.46	4.3955	650.4261	0.2818	0.8437	0.4587
DC215GRC	DC	1994	ERD	3/9/95	10929	RFG	12.04	5.5911	726.4299	0.2842	0.868	0.6711
DC216GRC	DC	1994	ERD	3/6/95	10076	RFG	13.35	4.8218	654.5357	0.2743	0.5952	0.4865
NJ201GRC	NJ	1992	ERD	10/13/94	20423	RFG	12.43	8.1747	698.3369	0.4139	0.6588	0.7744
NJ202GRC	NJ	1992	ERD	10/12/94	12381	RFG	12.21	9.3336	709.1657	0.4342	0.6041	0.8197
NJ203GRC	NJ	1992	ERD	10/14/94	15463	RFG	12.56	7.6116	691.9962	0.3387	0.6483	1.0386
NY201GRC	NY	1992	ERD	10/21/94	3550	RFG	12.23	4.5631	715.5107	0.265	0.3939	0.7587
NY202GRC	NY	1992	ERD	10/20/94	13879	RFG	13.14	7.3946	660.9835	0.3497	1.0246	0.8348
DC201GRC	DC	1994	ERD	5/4/95	24669	RFG	13.55	9.6833	636.6532	0.3847	0.9825	0.6808
DC206GRC	DC	1994	ERD	5/11/95	11593	RFG	13.12	5.0581	666.334	0.2564	0.6761	0.4999
DC217GRC	DC	1994	ERD	4/19/95	10946	RFG	13.33	4.7994	656.4014	0.2664	0.8582	0.417
DC219GRC	DC	1994	ERD	4/14/95	9731	RFG	13.26	5.1167	658.5522	0.2621	0.7596	0.3524

DV203CR	DV	1992	MAN	7/15/94	22245	CNG	13.412	0.394	506.8935	0.0354	1.6684	•
DV203CR	DV	1992	MAN	7/17/94	22272	CNG	13.5854	0.6207	499.834	0.067	1.433	•
DV205CR	DV	1992	MAN	5/16/94	10107	CNG	13.1203	2.1215	515.0817	0.1488	0.2565	•
DV205CR	DV	1992	MAN	5/18/94	10141	CNG	13.0257	1.3145	519.9444	0.0849	0.3631	•
DV208CR	DV	1992	MAN	6/15/94	4180	CNG	13.4482	2.2634	503.4215	0.0257	0.2988	•
DV209CR	DV	1992	MAN	6/10/94	3607	CNG	13.3064	2.2416	508.8965	0.0223	0.1724	•
DV210CR	DV	1992	MAN	7/1/94	4830	CNG	13.7433	2.1915	492.384	0.0531	0.2055	•
DV211CR	DV	1992	MAN	3/7/95	4342	CNG	13.0919	7.3207	507.2388	0.0398	0.297	0.2892
DV214CR	DV	1992	MAN	3/14/95	5790	CNG	12.5123	3.3715	539.2654	0.0408	0.1449	0.5133
DV216CR	DV	1992	MAN	6/2/94	19633	CNG	13.6543	2.1307	494.8459	0.0558	0.4079	•
DV217CR	DV	1992	MAN	4/27/94	4253	CNG	13.4696	1.2116	503.5414	0.085	0.4094	•
DV217CR	DV	1992	MAN	5/11/94	4302	CNG	13.149	0.8014	516.2777	0.1215	0.5035	•
DV218CR	DV	1992	MAN	3/7/95	5647	CNG	13.5748	2.4929	497.8253	0.0353	0.4935	•
DV219CR	DV	1992	MAN	2/22/95	2121	CNG	12.8361	1.2628	529.3326	0.023	0.0858	0.2223
DV204CR	DV	1992	MAN	2/16/95	5271	CNG	13.3231	18.3081	479.167	0.1836	1.3804	•
DV206CR	DV	1992	MAN	4/4/95	4522	CNG	13.1898	4.2485	509.888	0.037	0.1124	2.5033
DV207CR	DV	1992	MAN	4/6/95	12349	CNG	13.7581	3.4047	490.0819	0.0272	0.1718	0.3067
DV212CR	DV	1992	MAN	3/1/95	9514	CNG	15.5465	0.7192	436.6604	0.0602	0.9169	0.0877
DV220CR	DV	1992	MAN	4/11/95	7991	CNG	13.6469	5.2411	489.5521	0.0504	0.7511	0.0587
DC201CR	DC	1992	ERD	12/9/94	6373	CNG	11.47	1.6191	567.5223	0.0504	0.2067	0.1396
DC202CR	DC	1992	ERD	4/20/94	4906	CNG	12.17	2.2326	533.5688	0.0258	0.3293	•
DC202CR	DC	1992	ERD	4/21/94	4925	CNG	12.19	1.3078	535.4055	0.0227	0.5532	•
DC203CR	DC	1992	ERD	11/15/94	4108	CNG	11.55	1.326	563.8011	0.067	0.633	1.4556
DC204CR	DC	1992	ERD	12/6/94	15026	CNG	11.82	3.6231	546.9124	0.0422	0.5234	0.5909
DC205CR	DC	1992	ERD	9/1/94	3220	CNG	11.55	2.3676	561.8193	0.043	0.1473	•
DC208CR	DC	1992	ERD	4/12/94	4382	CNG	12.37	1.416	527.4893	0.0364	0.3378	•
DC208CR	DC	1992	ERD	4/13/94	4407	CNG	12.43	1.1212	524.709	0.0344	0.4094	•
DC210CR	DC	1992	ERD	11/29/94	9492	CNG	11.61	0.4693	562.3634	0.0413	1.2035	0.2509
DC211CR	DC	1992	ERD	5/13/94	5481	CNG	11.73	1.8766	553.9037	0.0767	0.3722	•
DC212CR	DC	1992	ERD	11/15/94	6595	CNG	11.11	1.5938	586.6979	0.039	0.2991	0.0566
DC213CR	DC	1992	ERD	12/8/94	9361	CNG	11.62	0.9947	562.2017	0.0256	0.523	0.2844
DC214CR	DC	1992	ERD	12/15/94	3207	CNG	11.15	2.1205	582.91	0.055	0.071	1.3672
DC216CR	DC	1992	ERD	12/14/94	15091	CNG	11.64	4.7964	553.6522	0.1007	0.3217	0.158
DC220CR	DC	1992	ERD	11/17/94	10091	CNG	11.53	0.8387	566.825	0.023	0.3908	0.1409
NJ201CR	NJ	1992	ERD	11/3/94	4477	CNG	11	3.8278	583.2373	0.06	0.8269	0.2618
NJ202CR	NJ	1992	ERD	11/7/94	13954	CNG	11.4	2.9097	568.1722	0.0491	0.6302	0.1384
NJ203CR	NJ	1992	ERD	11/4/94	12458	CNG	11.43	1.5886	569.1654	0.0616	0.9593	0.3544
NY201CR	NY	1992	ERD	10/27/94	3951	CNG	11.15	3.637	579.288	0.0485	0.1366	0.8547
NY202CR	NY	1992	ERD	10/28/94	7717	CNG	11.49	1.0538	566.9647	0.0464	0.7234	0.085
DC222CR	DC	1994	ERD	11/17/94	4771	CNG	11.6	0.8227	562.725	0.0495	0.9348	0.0532
DC223CR	DC	1994	ERD	12/1/94	10435	CNG	11.51	2.6836	564.4001	0.0429	0.528	0.1617
DC224CR	DC	1994	ERD	12/2/94	6935	CNG	11.44	0.7064	571.2047	0.0519	1.0336	0.1286

Table A2. Toxic emissions and speciated hydrocarbons

VEHICLE ID	HOME SITE	MODEL YEAR	LAB	TEST DATE	ODOMETER	FUEL	C_6H_6	C_4H_6	HCHO	CH_3CHO	OFP	SR
DV209GRC	DV	1992	MAN	4/18/95	10123	RFG	10.1	1.9	3.66	1.03	1102.1178	4.017
DV213GRC	DV	1992	MAN	4/25/95	9300	RFG	11.3	1.9	3.86	1.42	1181.4786	4.203
DV214GRC	DV	1992	MAN	4/27/95	7287	RFG	9.5	2	2.26	0.61	1164.6205	4.01
DV204CR	DV	1992	MAN	2/16/95	5271	CNG	1.1	0.2	10.78	0.71	487.5246	2.394
DV212CR	DV	1992	MAN	3/1/95	9514	CNG	0.3	0	1.78	0.07	100.575	1.684